

# Galaxy groups in the 2dFGRS: the luminous content of the groups

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2 February 2008

## ABSTRACT

The 2dFGRS Percolation-Inferred Galaxy Group (2PIGG) catalogue of  $\sim 29000$  objects is used to study the luminous content of galaxy systems of various sizes. Mock galaxy catalogues constructed from cosmological simulations are used to gauge the accuracy with which intrinsic group properties can be recovered. It is found that a Schechter function is a reasonable fit to the galaxy luminosity functions in groups of different mass in the real data, and that the characteristic luminosity  $L_*$  is larger for more massive groups. However, the mock data show that the shape of the recovered luminosity function is expected to differ from the true shape, and this must be allowed for when interpreting the data. Luminosity function results are presented in both the  $b_J$  and  $r_F$  wavebands. The variation of halo mass-to-light ratio,  $\Upsilon$ , with group size is studied in both these wavebands. A robust trend of increasing  $\Upsilon$  with increasing group luminosity is found in the 2PIGG data. Going from groups with  $b_J$  luminosities equal to  $10^{10} h^{-2} L_\odot$  to those 100 times more luminous, the typical  $b_J$ -band mass-to-light ratio increases by a factor of 5, whereas the  $r_F$ -band mass-to-light ratio grows by a factor of 3.5. These trends agree well with the predictions of the simulations which also predict a minimum in the mass-to-light ratio on a scale roughly corresponding to the Local Group. Our data indicate that if such a minimum exists, then it must occur at  $L \lesssim 10^{10} h^{-2} L_\odot$ , below the range accurately probed by the 2PIGG catalogue. According to the mock data, the  $b_J$  mass-to-light ratios of the largest groups are expected to be approximately 1.1 times the global value. Assuming that this correction applies to the real data, the mean  $b_J$  luminosity density of the Universe yields an estimate of  $\Omega_m = 0.26 \pm 0.03$ . Various possible sources of systematic error are considered, with the conclusion that these can affect the estimate of  $\Omega_m$  by up to 20%.

**Key words:** galaxies: groups – galaxies: haloes – galaxies: clusters: general – large-scale structure of Universe.

## 1 INTRODUCTION

The distribution of galaxy luminosities, along with their mass-to-light ratios and spatial distribution, represent key observations that should be explained by theories of galaxy formation. In the  $\Lambda$ CDM model of structure formation, these broad brush empirical characterisations of the galaxy population result from a complicated interplay between the lumpy growth and coalescence of dark matter haloes and the radiative cooling, star formation and feedback associated with baryons within these clumps. Not only are the galaxies signposts to locate the underlying overdensities in the dark matter distribution, their properties also provide a systematic record of the processes that have taken place in those haloes and their progenitors. To develop a deeper understanding of the impact of these various processes, it is helpful to break down the global constraints referred to above and consider their variation with halo mass.

The determination of the luminosity function of galaxies has received much observational effort (e.g. Blanton et al. 2001, 2003; Cole et al. 2001; Kochanek et al. 2001; Norberg et al. 2002), and recently there have been suggestions that the distribution of galaxy luminosities varies between rich cluster environments and low density regions (e.g. Zabludoff & Mulchaey 2000; Christlein 2000; Balogh et al. 2001; de Propris et al. 2003). Furthermore, some authors find evidence that a Schechter function does not well describe the galaxy luminosity function in groups and clusters because of an excess of bright galaxies (e.g. Smith, Driver & Phillipps 1997; Trentham & Tully 2002; Christlein & Zabludoff 2003). While these empirical results are intriguing, a systematic study with a large set of homogenous groups would add welcome weight to these findings. What should one expect to find? This question has been addressed using semi-analytical prescriptions (White & Frenk 1991; Kauffmann et al. 1993; Diaferio et al. 1999; Benson et al. 2003b). These techniques provide a physically motivated *ab initio* procedure for calculating the properties of galaxy populations, which can be compared with the real Universe in order to constrain the physical processes and their implementation within the models. Both Diaferio et al. and Benson et al. find that the galaxy luminosity functions within haloes of different mass are not well described by Schechter functions. Instead, they have an excess in the abundance at the bright end which arises from the different processes that are important for the growth of the large central galaxy relative to the other galaxies in the haloes (the satellites). In smaller haloes, where a larger fraction of the group luminosity is typically locked up in the central galaxy, this produces a more prominent deviation from a Schechter function at the bright end of the group's galaxy luminosity function. Furthermore, the luminosity at which this 'central galaxy bump' occurs, increases with halo mass. Testing the predictions from these models represents an opportunity to learn about aspects of galaxy formation.

The mass-to-light ratios ( $\Upsilon$ ) of groups represent another important clue, the light-to-mass ratio essentially reflecting the efficiency with which stars are formed within haloes of different mass. In large haloes this should be determined by the rate of gas cooling, whereas in small haloes other factors that cause energy to be injected into the halo gas become effective at disrupting the formation of stars. The prediction of semi-analytical models is that mass should be

converted most efficiently into optical light in haloes of mass  $\sim 10^{12} h^{-1} M_{\odot}$  (White & Frenk 1991; Kauffmann et al. 1999; Benson et al. 2000). One way in which this can be tested is to take a theoretically motivated mass function and match haloes with galaxy groups of the same abundance as inferred from an empirically determined group luminosity function. This reveals the variation of the typical  $\Upsilon$  with mass. Qualitatively, Marinoni & Hudson (2002) find a trend similar to that predicted by semi-analytical models, namely a minimum  $\Upsilon$  at intermediate masses of  $\sim 10^{12} h^{-1} M_{\odot}$ . Observationally, there have been many studies that have directly measured  $\Upsilon$  for clusters and large groups of galaxies in various wavebands ( $R$  – Carlberg et al. 1996, 2001; Tucker et al. 2000;  $V$  – Schaeffer et al. 1993; David, Jones & Forman 1995; Cirimele, Nesci & Trèvese 1997; Hradecky et al. 2000;  $B$  – Ramella, Pisani & Geller 1997; Adami et al. 1998; Girardi et al. 2000, 2002; Sanderson & Ponman 2003; Tully 2004). Some studies suggest that the mass-to-light ratio is larger in bigger systems, whereas other studies find no significant variation.

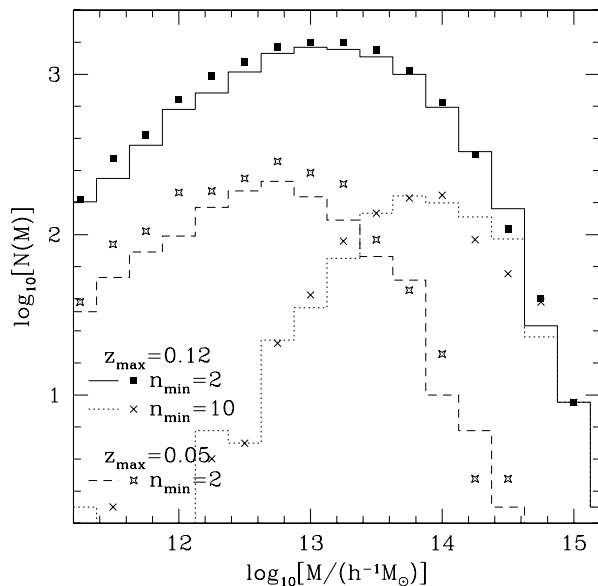
In addition to the direct relevance of the mass-to-light ratio and its dependence on halo mass for studies of galaxy formation,  $\Upsilon$  is an important quantity to measure since it provides one of the traditional ways to estimate the mean matter density of the Universe (e.g. Carlberg et al. 1996). This requires an assumption about the relation between the mass-to-light ratio of the groups or clusters and the mean cosmic value. Traditionally, it has been assumed that the value of  $\Upsilon$  for the most massive clusters is representative of the universal mean, although for a long time this assumption was challenged in biased models of galaxy formation (Davis et al. 1985). At any rate, the value of  $\Upsilon$  for clusters, together with an appropriate assumption about its universality and knowledge of the total galaxy luminosity density allows a simple estimate of the mean mass density for the Universe.

The construction of the 2dFGRS Percolation-Inferred Galaxy Group (2PIGG) catalogue (Eke et al. 2004) from the 2 degree Field Galaxy Redshift Survey (2dFGRS: Colless et al. 2001, 2003) facilitates a direct calculation of the galaxy content in a large sample of homogenous groups. The purpose of this paper is to report the results of a decomposition, by group size, of the luminosity functions of galaxies within groups, and the group mass-to-light ratio. Mock catalogues constructed from cosmological simulations are employed as a guide to the accuracy with which these quantities can be inferred from the 2PIGG sample. This is a vital step in the comparison of a model prediction with the observational results.

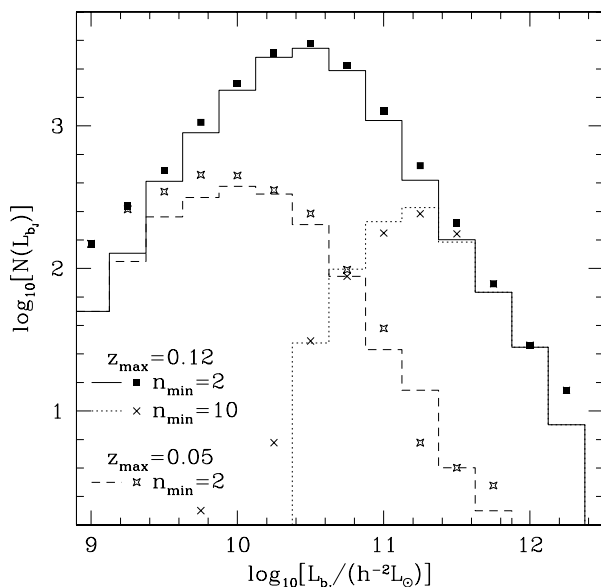
Section 2 contains a brief description of the group catalogue and a quantitative study of its reliability. In Section 3 the luminosity functions of galaxies within groups is shown for different halo masses. The variation of total halo mass-to-light ratio with halo size is investigated in Section 4.

## 2 INFERRED GROUP PROPERTIES

A detailed description of the construction of the mock catalogues, and the groupfinding algorithm applied both to these and the real 2dFGRS was given by Eke et al. (2004). Briefly, three different  $\Lambda$ CDM dark matter N-body simulations were used. They had  $(L, N_p, \sigma_8) = (154, 288^3, 0.7)$ ,  $(250, 500^3,$



**Figure 1.** The number of groups at  $z < 0.12$  and  $z < 0.05$  as a function of the group dynamical mass,  $M$ . Solid and dotted lines correspond to the mock catalogues with  $z_{\max} = 0.12$  and  $n_{\min} = 2$  and 10 respectively. Filled squares and crosses are likewise for the 2PIGG catalogue. The dashed line is for  $z_{\max} = 0.05$  and  $n_{\min} = 2$ , and the corresponding result from the real catalogue is shown with stars.



**Figure 2.** The number of groups as a function of the total group  $b_J$  band luminosity,  $L_{b_J}$ . The lines and symbols have the same meaning as in Fig. 1.

0.8) and  $(141, 256^3, 0.9)$ , where  $L$  is the side of the computational cube in  $h^{-1}$  Mpc,  $N_p$  the number of particles and  $\sigma_8$  the rms linear density fluctuation in  $8 h^{-1}$  Mpc spheres. (The last of these is the GIF simulation described in Jenkins et al. 1998.) The semi-analytical model of galaxy formation described by Cole et al. (2000) was implemented in the simulations to create populations of model galaxies whose observable properties are given by the model.

Although the semi-analytical model produces a galaxy luminosity function which is quite similar to that in the 2dFGRS, a small rescaling of the  $b_J$  luminosities was applied, to produce a model luminosity function which was identical to that in the 2dFGRS. Mock 2dFGRS catalogues were then constructed with the same geometry and position-dependent flux limit as the 2dFGRS, and samples of groups were selected by applying exactly the same cluster-finding algorithm used to generate the 2PIGG catalogue. The  $r_F$  band magnitudes were rescaled in the same way as those in the  $b_J$  band, preserving the semi-analytical galaxy colours. Unlike in the  $b_J$  band, the resulting galaxy  $r_F$ -band luminosity functions for the mock and 2dFGRS catalogues are thus not identical, as detailed in Appendix A.

Here, the focus is on describing the pertinent group properties and quantifying the accuracy with which they are inferred. The latter relies entirely on the mock catalogues, for which the true properties of the haloes hosting the groups are known in the parent simulation.

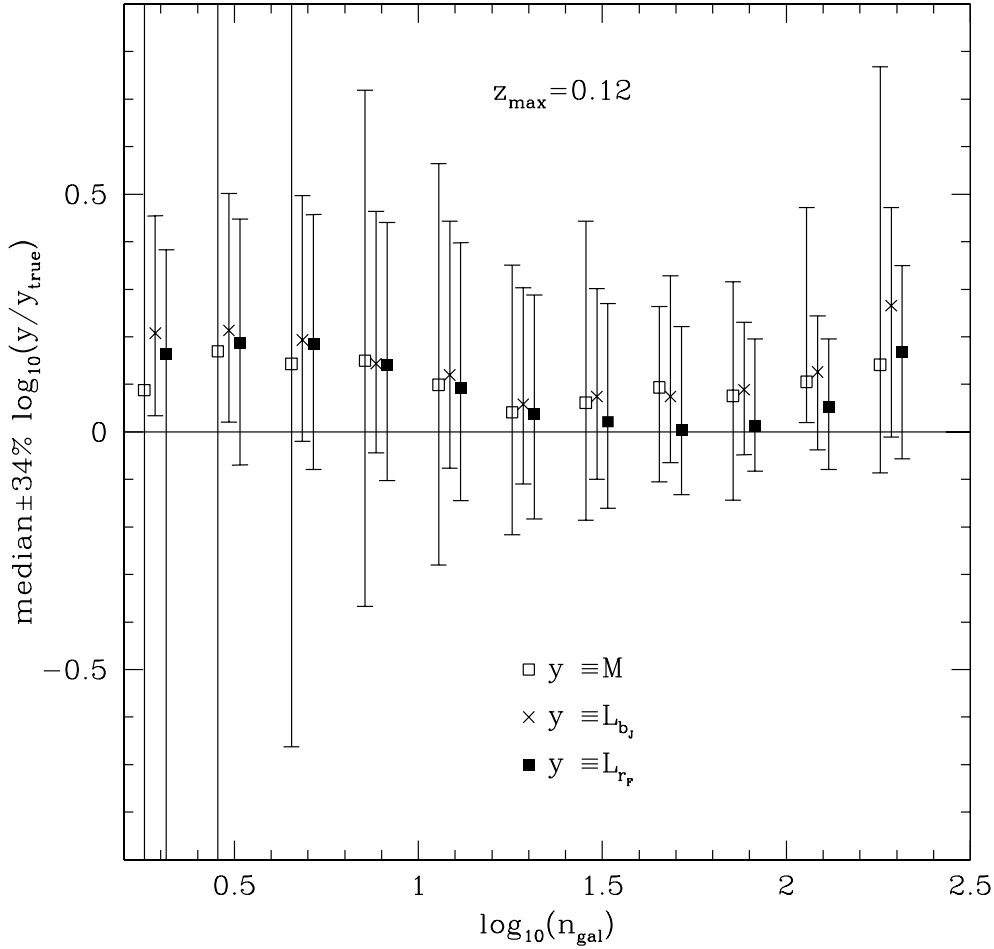
As described by Eke et al. (2004), the group mass is inferred dynamically according to

$$M = A \frac{\sigma^2 r}{G}, \quad (2.1)$$

where  $A = 5.0$ ,  $\sigma$  is the 1-dimensional velocity dispersion, calculated using the gapper algorithm (Beers, Flynn & Gebhardt 1990) and removing  $85 \text{ km s}^{-1}$  in quadrature to account for redshift measurement errors, and  $r$  is the r.m.s. projected separation of galaxies from the group centre, assuming an  $\Omega_m = 0.3, \Omega_\Lambda = 0.7$  cosmological model. The value of  $A$  has been chosen by reference to mock catalogues in which galaxies trace the dark matter within each halo, apart from a ‘central’ galaxy placed at the halo centre of mass. There is some evidence from gravitational lensing studies that bright galaxies do indeed trace the mass, at least in rich clusters (Hoekstra et al. 2002; Kneib et al. 2003). However, these current observational constraints are not yet sufficiently stringent that the effective value of  $A$  can be empirically justified to better than a few tens of per cent. This is the main potential source of systematic error in this paper.

## 2.1 Calculating group luminosities

In order to calculate the total group luminosity, it is necessary to correct for the incompleteness in the 2dFGRS. When finding the groups, galaxies from the parent catalogue that have no measured redshift have their weights redistributed equally to the nearest 10 projected galaxies with measured redshifts, and these galaxies are assigned a larger linking volume accordingly. As the sets of galaxies with and without redshifts are random subsamples (in terms of the intrinsic galaxy properties) of the same underlying galaxy population (ignoring the small level of flux-dependent redshift in-



**Figure 3.** The median accuracies (symbols)  $\pm 34$  percentiles (error bars) of the inferred group properties as a function of the number of galaxies in a group,  $n_{\text{gal}}$ . All groups with  $z \leq 0.12$  are included. The symbols correspond to the following group properties:  $y = M$  (open squares),  $L_{b_J}$  (crosses) and  $L_{r_F}$  (filled squares). The points have been slightly displaced either side of the true bin values for clarity.

completeness), the incompleteness can simply be taken into account by totting up the observed group  $b_J$  luminosity according to

$$L_{\text{obs}, b_J} = \sum_i^{n_{\text{gal}}} w_i L_{i, b_J}, \quad (2.2)$$

where the sum extends over the  $n_{\text{gal}}$  galaxies in the group with their individual weights,  $w_i$ . The total group luminosity is then estimated by including the contribution from galaxies below the luminosity limit,  $L_{\text{min}}$ , at the redshift of the group. The extrapolation to zero galaxy luminosity is performed assuming that a Schechter function describes the number of galaxies as a function of luminosity. Given that the Schechter function is

$$\phi(L)dL = \phi_* \left( \frac{L}{L_*} \right)^\alpha \exp \left( -\frac{L}{L_*} \right) \frac{dL}{L_*}, \quad (2.3)$$

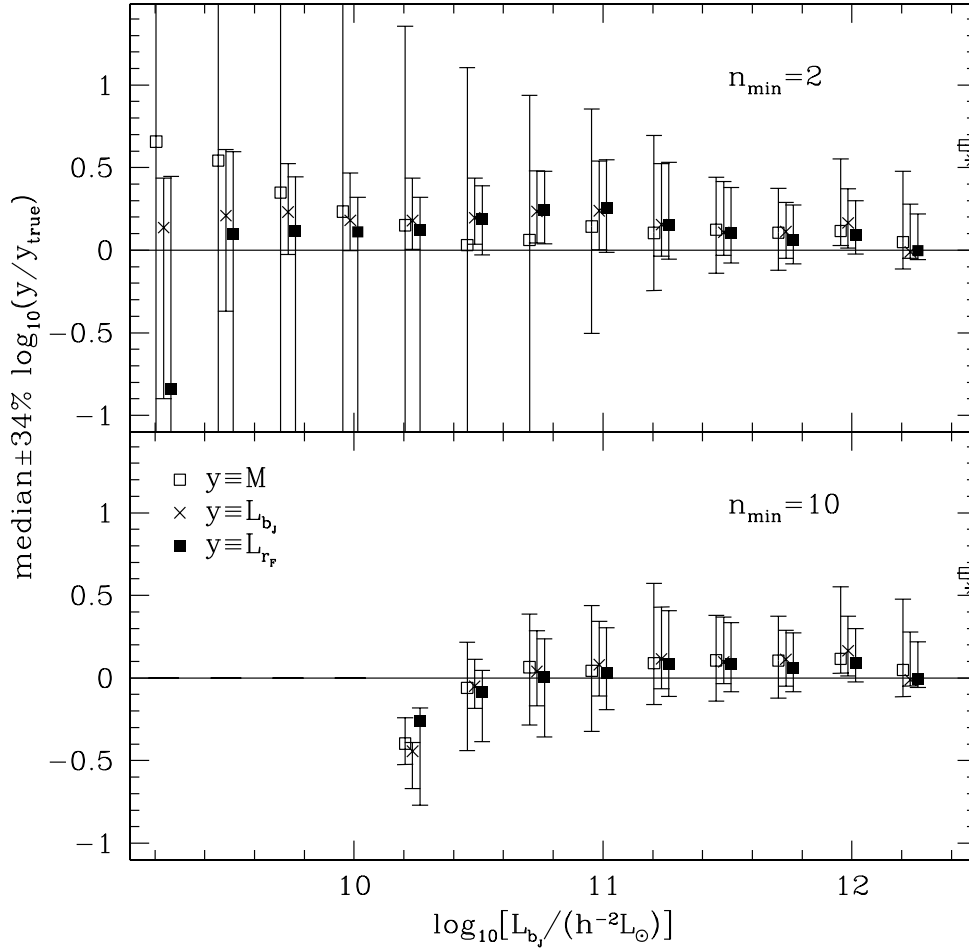
this operation merely involves dividing the observed luminosity by the incomplete Gamma function  $\Gamma(\alpha + 2, L_{\text{min}}/L_*)/\Gamma(\alpha + 2)$ . In practice, a small correction is also applied because galaxies with fluxes corresponding to  $b_J < 14$  have been removed from the redshift catalogue. This bright flux limit only makes a perceptible difference for a few

very local groups. These calculations require the additional information that  $M_\odot = 5.33$  in the  $b_J$  band and the adopted  $k + e$ -correction is similar to that of Norberg et al. (2002),

$$k + e = \frac{z + 6z^2}{1 + 8.9z^{2.5}}. \quad (2.4)$$

The global  $(M_*, \alpha) = (-19.725, -1.18)$  values are used to extrapolate to the total luminosity for all groups. These values differ slightly from those of Norberg et al. (2002) as they have been derived from the recalibrated 2dFGRS (Colless et al. 2003). Using a halo mass-dependent extrapolation (see Section 3) changes the inferred luminosities by no more than  $\sim 10$  per cent.

At  $z > 0.12$ , the fraction of the total group luminosity that is actually observed drops below a half. Additionally, according to the mock catalogues, the amount of contamination of group membership increases at these higher redshifts. Thus, in all of what follows, only groups at  $z < 0.12$  will be considered. This provides a large number of well-sampled groups with a range of masses up to  $\sim 10^{15} h^{-1} M_\odot$ . The number of groups as a function of mass and luminosity is shown in Figs 1 and 2 for both the mock and real catalogues,



**Figure 4.** The median accuracies (symbols)  $\pm 34$  percentiles of the inferred group properties as a function of the inferred group luminosity,  $L_{b_J}$ . In the top panel,  $n_{\min} = 2$  and, in the bottom panel,  $n_{\min} = 10$ . Each bundle of three symbols has the following order from left to right:  $y = M$ ,  $L_{b_J}$  and  $L_{r_F}$ . The points have been slightly displaced either side of the true bin values for clarity.

choosing the minimum group membership to be  $n_{\min} = 2$  or 10. Distributions of  $n_{\min} = 2$  groups at  $z < 0.05$  are also shown in these figures. The mock and real catalogues yield broadly similar numbers of groups with similar masses and luminosities. There is a slight deficit of groups in the mock catalogue relative to the 2PIGG data. This originates from the lack of low luminosity galaxies included at  $z < 0.04$ , as described by Eke et al. (2004).

Complications arise when using the SuperCOSMOS (Hambly et al. 2001)  $r_F$  band data because the 2dFGRS is a  $b_J$  selected survey. Different depths in the red luminosity function are thus probed for galaxies of different spectral types. Rather than dealing with the explicit dependence of the luminosity function on colour, the sample was re-cut to a conservative  $r_F$  limit such that almost all 2dFGRS galaxies can be detected to the same red luminosity at a given redshift. This issue is discussed in detail in Appendix A, which justifies re-cutting the sample at a local limit of  $r_{F,\text{lim}} = b_{J,\text{lim}} - 1.5$ .

## 2.2 The accuracy of measured halo properties

The typical redshift error in the 2dFGRS of  $\sim 85 \text{ km s}^{-1}$  (Colless et al. 2001) will lead to small mass haloes having considerable errors in their estimated velocity dispersions and hence masses. For instance,  $\sigma = 85 \text{ km s}^{-1}$  and  $r = 100 h^{-1} \text{ kpc}$  correspond to a mass of about  $10^{12} h^{-1} M_{\odot}$ . In order to interpret the results in the following sections, it is important to quantify the degree of uncertainty in the estimated halo masses and luminosities and how this varies with properties such as the number of member galaxies,  $n_{\text{gal}}$ , or halo luminosity.

The ‘accuracy’ with which a halo property is measured is defined as a logarithmic measure of the error in the property:

$$\text{accuracy} \equiv \log_{10} \left( \frac{y_{\text{recovered}}}{y_{\text{true}}} \right), \quad (2.5)$$

where  $y$  can stand for mass,  $b_J$  or  $r_F$  luminosity. Figs 3 and 4 show how the median accuracies, and the 16th and 84th percentiles (as opposed to the mean  $\pm 1\sigma$ ), vary as functions of  $n_{\text{gal}}$  and  $L_{b_J}$  respectively. Fig. 3 shows that the spread

in mass accuracies becomes very large when the number of group members is less than 10. For more populated groups, the median accuracy is approximately zero, meaning that the typical inferred mass is unbiased. The luminosities are typically overestimated by a few tens of per cent even for well-populated groups, but they can still be relatively well determined for binaries. From this figure, one can infer that measured group luminosity is a better quantity than the measured dynamical mass for ranking the groups in order of size. Note that the accuracy of  $r_F$  luminosities has a larger spread than that in the  $b_J$  band. This is the result of using fewer galaxies to calculate the  $r_F$  luminosity, meaning that the Schechter function correction for unobserved galaxies is slightly larger in the  $r_F$  than in the  $b_J$  band. Similar trends are visible in Fig. 4, where the distributions of accuracies are shown as a function of group luminosity for two different values of  $n_{\min}$ . At low group luminosity, particularly for  $n_{\min} = 2$ , the halo masses become increasingly overestimated and poorly determined due to the impact of the 2dFGRS redshift errors and contamination. Also apparent is a tail of underestimated group  $r_F$  luminosities at low  $b_J$  group luminosity. These are binary groups with no members that satisfy the adopted flux limits, and are thus assigned zero  $r_F$ -band luminosity.

Armed with this quantitative understanding of the group catalogue, it is now appropriate to see what information can be extracted concerning the galaxy populations in different sizes of halo.

### 3 GALAXY LUMINOSITY FUNCTIONS WITHIN GROUPS

This Section addresses firstly the issue of how well the galaxy luminosity function in haloes of different mass can be recovered from the mock catalogues and, secondly, the determination of these functions for the real data. In calculating the space density of galaxies, a  $1/V_{\max}$  estimator has been applied to each galaxy. The variable flux limit across the survey has been taken into account. Dynamically inferred group masses, calculated according to equation (2.1), have been used to split the total sample into different classes.

#### 3.1 $b_J$ band results

Sets of mock catalogues have been constructed from two different semi-analytical models of galaxy formation applied to the same N-body simulations. Both these models are based on the general scheme developed by Cole et al. (2000), but they treat certain physical processes in different ways. The first model, described by Benson et al. (2002), is very similar to the original Cole et al. model except that it includes detailed treatments of photoionization of the intergalactic medium at high redshift and of the dynamics of satellites in haloes. This model, which will be referred to as the ‘bumpy’ model for reasons that will become apparent shortly, was used by Benson et al. (2003b) to predict the luminosity function of galaxies in haloes of different mass. The second model comes from Benson et al. (2003a) and will be referred to as the ‘superwind’ model. This has a baryon fraction twice as high as that assumed by Cole et al., in

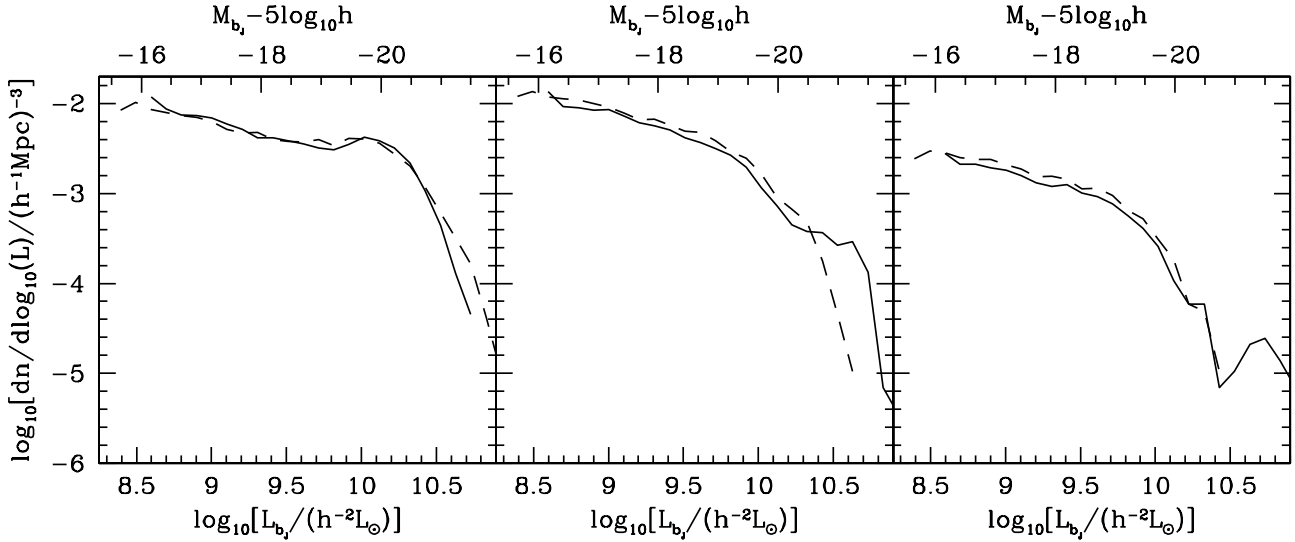
accordance with recent determinations, and includes a treatment of superwinds. These suppress the growth of the overly bright galaxies which otherwise tend to form in high baryon fraction models.

Fig. 5 shows galaxy luminosity functions in groups of different mass in both the semi-analytical models of galaxy formation. The solid lines correspond to the bumpy model while the dashed lines correspond to the superwind model. The suppression of bright central galaxies in the superwind model is apparent in the middle and right-hand panels which show the galaxy luminosity functions within groups of mass  $M \sim 10^{14} h^{-1} M_{\odot}$  and  $M \sim 10^{15} h^{-1} M_{\odot}$  respectively. It is clear that the detailed shapes of the galaxy luminosity functions in groups depend upon the assumptions that go into making a semi-analytical model. These data can thus be used to test the models. In what follows, the bumpy mock catalogues will be shown unless otherwise stated.

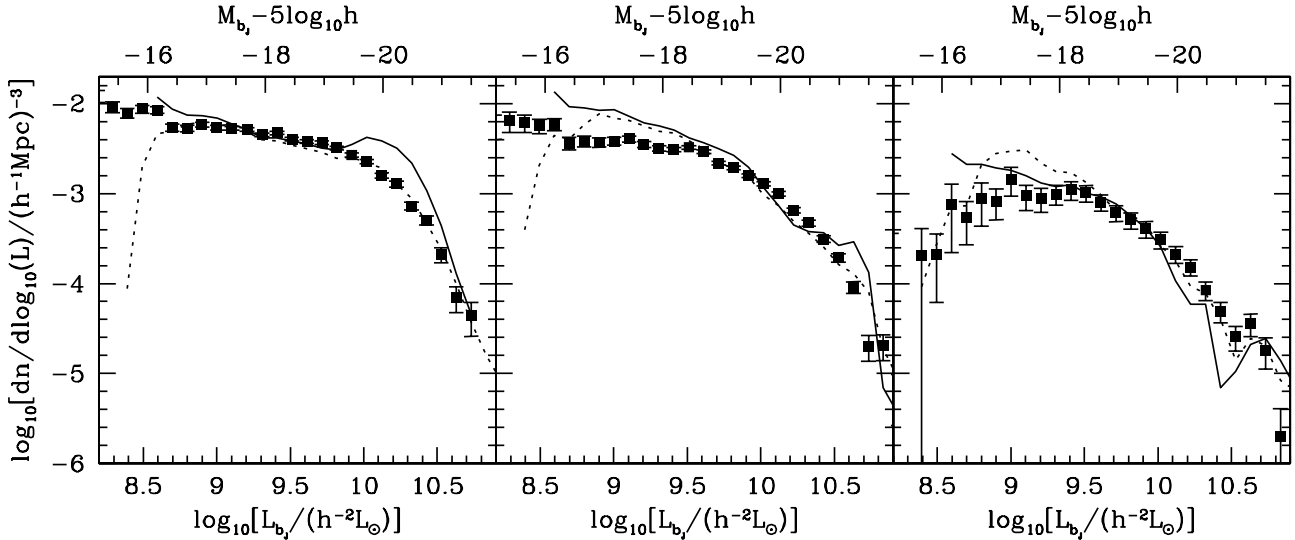
In order to recover faithfully both the amplitude and shape of the galaxy luminosity function in groups of different mass, it is helpful to adopt separate values of  $n_{\min}$  and  $z_{\max}$  for the various group samples. For instance, clusters that should contribute to the highest mass bin will have large numbers of members and be detectable to higher redshifts compared to the smaller groups. Thus, the following empirical choices of  $(n_{\min}, z_{\max})$  were made for the  $10^{13}$ ,  $10^{14}$  and  $10^{15} h^{-1} M_{\odot}$  samples respectively:  $[(3, 0.08), (10, 0.12), (80, 0.12)]$ . These will be used throughout this Section.

The results of these selections can be seen in Fig. 6, which shows the semi-analytical model luminosity functions in the simulations from which the mock catalogues were created, the luminosity functions actually recovered from the mocks, and the luminosity functions estimated from the 2PIGG sample for the same values of  $n_{\min}$  and  $z_{\max}$ . While the theoretical luminosity functions in the simulations from which the mock catalogues were made differ substantially from Schechter functions, the bumps have been largely smeared out in the mock recovered luminosity functions, which now better resemble Schechter functions. This smearing is predominantly the result of contaminating galaxies contributing to haloes with inappropriate masses and homogenizing the samples. Note that the original bumps occur at luminosities that vary with halo mass. There is a tentative bump detection in the two higher mass group samples. This excess of luminous galaxies is sufficient to render the Schechter function a bad fit, although it does provide a good description of the results for the  $M \sim 10^{13} h^{-1} M_{\odot}$  groups. Overall however, apart from the smearing out of the central galaxy bumps, the shapes and amplitudes of the group galaxy luminosity functions are recovered well from the mock catalogue.

Having determined the efficiency with which group mass-dependent galaxy luminosity functions are recovered, it is now appropriate to consider the real data. The 2PIGG results are shown by the points in Fig. 6. Error bars are the Poisson errors on the number of groups contributing galaxies to each luminosity bin. In almost all respects, the real 2PIGG results look very similar to those recovered from the mock catalogue, shown as dotted lines. The main difference is the abundance of low luminosity ( $L < L_*/3$ ) galaxies in higher mass haloes. The mock groups contain more of these galaxies than are present in high mass 2PIGGs. This differ-



**Figure 5.** Galaxy  $b_J$  luminosity functions in haloes of different mass predicted by two semi-analytical models of galaxy formation. The panels refer to haloes with masses of  $10^x h^{-1} M_\odot$ , with  $x = 13 \pm 0.5$  (left),  $14 \pm 0.5$  (centre) and  $15 \pm 0.5$  (right). The scales at the top of the panels give the absolute  $b_J$  magnitude. Solid lines correspond to the ‘bumpy’ semi-analytical model, whereas dashed lines correspond to the ‘superwind’ model.



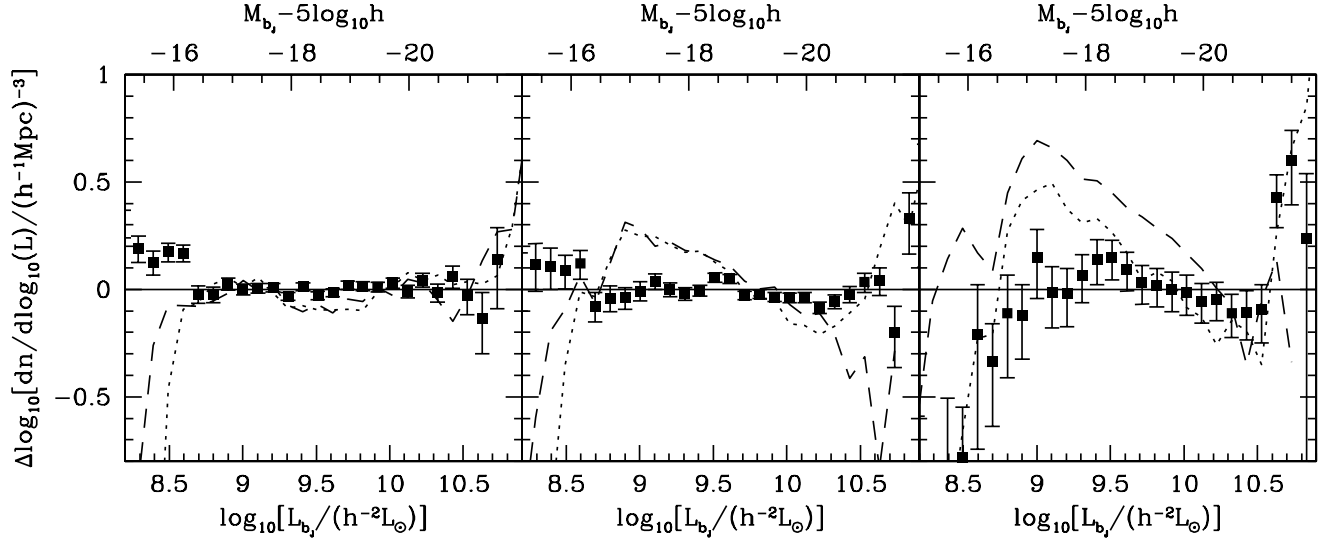
**Figure 6.** Galaxy  $b_J$  luminosity functions in groups of different mass in both mock and real 2PIGG catalogues. The group mass ranges are  $M \sim 10^{13} h^{-1} M_\odot$  (left),  $M \sim 10^{14} h^{-1} M_\odot$  (centre) and  $M \sim 10^{15} h^{-1} M_\odot$  (right). In each case, a solid line shows the semi-analytical prediction from which the mock catalogues were constructed, a dotted line shows what is actually measured in the mock groups, and the filled squares with errors depict the results from the 2PIGG data. The values of  $n_{\min}$  and  $z_{\max}$  are selected for each mass range, as described in the text, in order to optimize the recovery of the original galaxy semi-analytical luminosity functions.

ence is apparent in the panels showing the  $M \sim 10^{14} h^{-1} M_\odot$  and  $M \sim 10^{15} h^{-1} M_\odot$  results. The evidence for bumps in the 2PIGG data is also only tentative.

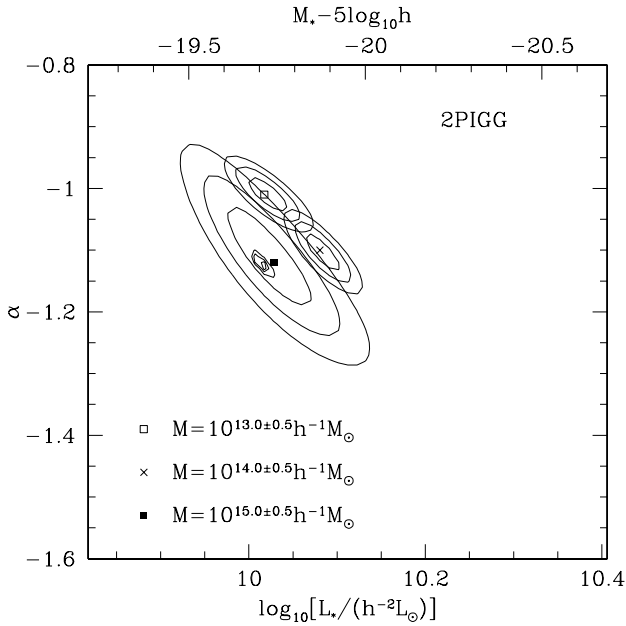
Fig. 7 shows the 1, 2 and 3- $\sigma$  contours in the  $L_* - \alpha$  plane for the STY (Sandage, Tammann & Yahil 1979) fits to the 2PIGG galaxy luminosity functions within groups of different mass. Also shown, without a symbol marking the most likely value, are the contours representing the best-fitting parameters for the whole galaxy population out to  $z = 0.12$ . The parameters for the highest mass bin are much

less well constrained because there are fewer total galaxies in these groups than in the more abundant, lower mass haloes. The 2PIGG sample has a slightly brighter  $L_*$  for the  $M \sim 10^{14} h^{-1} M_\odot$  groups than the  $M \sim 10^{13} h^{-1} M_\odot$  groups. This trend is reproduced in the bumpy mock catalogue but not in the superwind mock, in which the most luminous galaxies no longer reside in the most massive haloes.

Fig. 8 shows how the recovered luminosity functions differ from the suitably normalised best-fitting Schechter functions for the 2PIGGs. While the fit works well for both mock



**Figure 8.** The ratios of galaxy luminosity functions to the 2PIGG best-fitting Schechter functions for the  $M \sim 10^{13} h^{-1} M_{\odot}$  (left),  $M \sim 10^{14} h^{-1} M_{\odot}$  (centre) and  $M \sim 10^{15} h^{-1} M_{\odot}$  (right) groups. Results are shown for 2PIGG (squares), the bumpy mock (dotted lines) and the superwind mock (dashed lines).



**Figure 7.** 1, 2 and 3- $\sigma$  contours showing the relative probability that different Schechter function parameters,  $L_*$  and  $\alpha$ , provide a good description of the  $b_J$ -band galaxy luminosity function within 2PIGGs of different mass. These results were obtained by the STY estimation method using the groups contributing to the 2PIGG luminosity functions in Fig. 6. The different group masses have different symbols marking the most likely parameter values, as detailed in the figure. The small ellipses with no central symbol represent the results for all 2dFGRS galaxies at  $z < 0.12$ .

and real data in the  $M \sim 10^{13} h^{-1} M_{\odot}$  groups, it becomes an increasingly poor description in more massive systems, where an excess of luminous galaxies can be seen to distort the fit. Also apparent is the overabundance of low luminosity galaxies in the most massive mock groups relative to what

is found in the 2PIGGs. Finally, the lack of very luminous galaxies in the superwind mock shows that, despite the imperfections of the recovery, it is still possible to discriminate between this and the bumpy model.

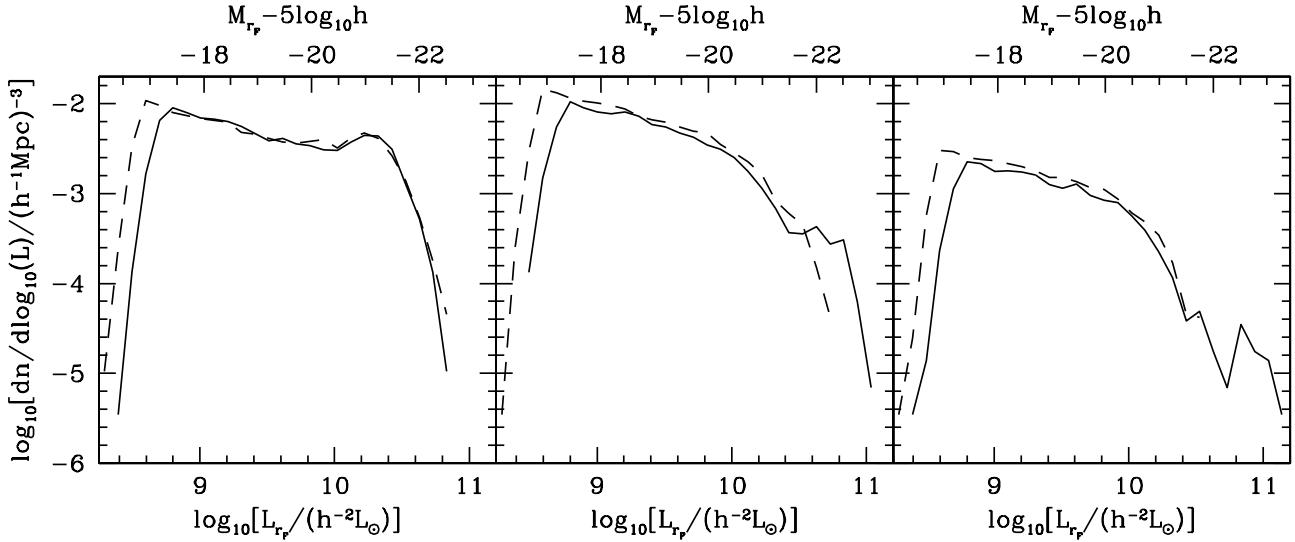
### 3.2 $r_F$ band results

The same analysis performed in Section 3.1 for the  $b_J$  band data can be performed for the  $r_F$  band data. While all galaxies can be used to calculate the luminosity functions using the  $1/V_{\max}$  method, the STY estimation of the best-fitting Schechter function parameters requires a complete sample, so galaxies are only included if  $14 < r_F < b_{J,\text{lim}} - 1.5$  when determining  $L_*$  and  $\alpha$ .

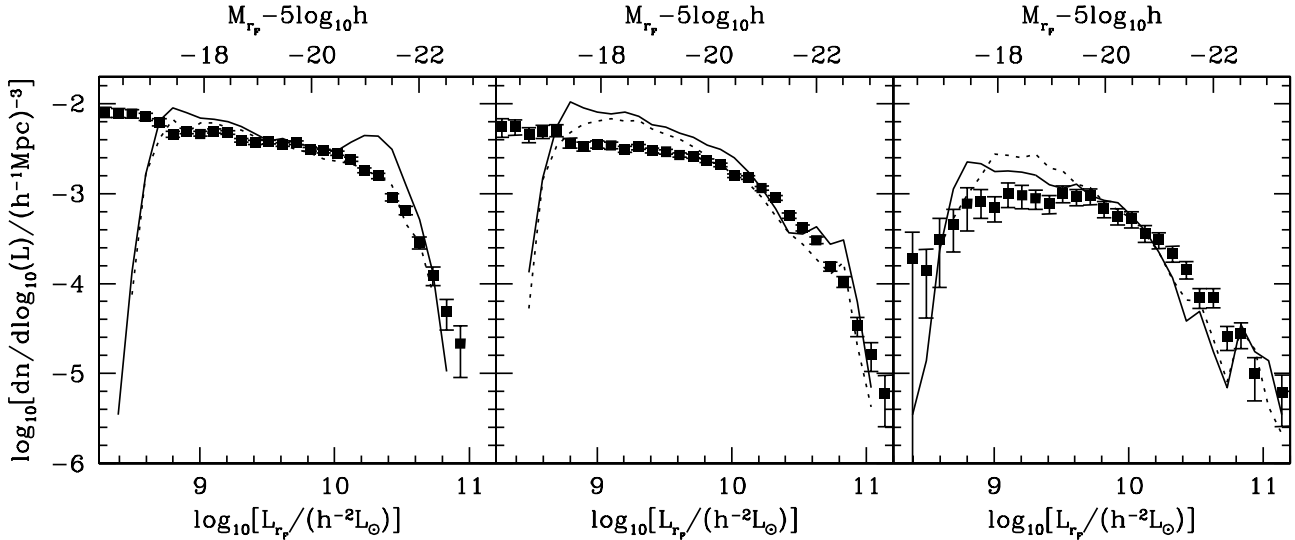
Figs 9, 10, 11 and 12 are the  $r_F$  band equivalents of the previous four figures for the  $b_J$  band. Apart from larger error ellipses on the recovered Schechter function fits, resulting from the smaller number of galaxies being used to ensure a complete sample, the  $r_F$  band results are qualitatively very similar to those found in the  $b_J$  band. The 2PIGGs with  $M \sim 10^{14} h^{-1} M_{\odot}$  again have an average galaxy luminosity function with  $L_*$  about 25 per cent higher than that for the  $M \sim 10^{13} h^{-1} M_{\odot}$  groups, and a slightly steeper faint end slope. The bumpy mock reproduces this scaling of  $L_*$  with halo mass, but again contains an excess of low luminosity galaxies in the most massive haloes. Once more, the superwind mock exhibits both an excess of low luminosity galaxies and a deficit of high luminosity galaxies in both of the higher mass bins, relative to the 2PIGG sample.

## 4 GROUP MASS-TO-LIGHT RATIOS

As outlined in the Introduction, the mass-to-light ratio of groups,  $\Upsilon$ , contains clues to the nature of galaxy formation, and it can also be used to estimate the mean mass density of the Universe. This Section contains a description of the



**Figure 9.** The  $r_F$  band equivalent of Fig. 5, showing the galaxy luminosity functions in groups of different mass in the two semi-analytical models of galaxy formation. As before, the panels correspond to groups with  $M = 10^{13 \pm 0.5} h^{-1} M_\odot$  (left),  $M = 10^{14 \pm 0.5} h^{-1} M_\odot$  (centre) and  $M = 10^{15 \pm 0.5} h^{-1} M_\odot$  (right). Solid lines correspond to the ‘bumpy’ semi-analytical model, whereas dashed lines correspond to the ‘superwind’ model.



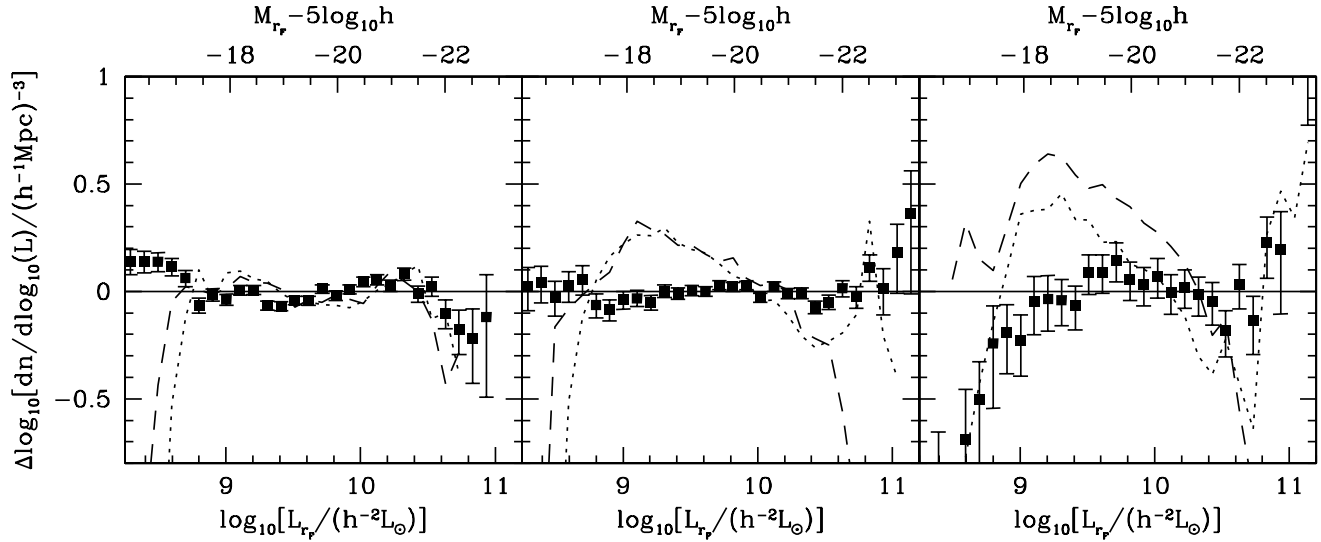
**Figure 10.** The  $r_F$  band equivalent of Fig. 6, showing both how well the galaxy luminosity functions can be recovered in different sized groups, and how the mock results compare with the real 2PIGG data. As before, the group mass ranges are  $M \sim 10^{13} h^{-1} M_\odot$  (left),  $M \sim 10^{14} h^{-1} M_\odot$  (centre) and  $M \sim 10^{15} h^{-1} M_\odot$  (right). In each case, a solid line shows the semi-analytical prediction from which the mock catalogues were constructed, a dotted line shows what is actually measured in the mock groups, and the filled squares with errors depict the results from the 2PIGG data.

accuracy with which  $\Upsilon$  can be determined from the 2PIGG catalogue, and addresses the dependence of  $\Upsilon$  on group luminosity, the size of halo in which stars form most efficiently, and the estimate of the mean mass density,  $\Omega_m$ .

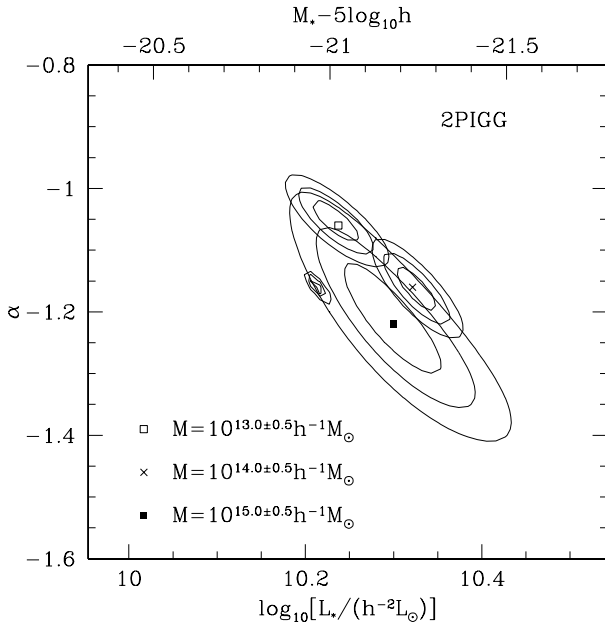
In trying to recover the typical group mass-to-light ratio for groups of a particular size, there is no reason to use the entire group sample. One merely requires an unbiased subset of groups. Experimentation with the mock catalogues has yielded an appropriate subset, in which the bias of the results is minimized. In this scheme, the smaller

groups are only used when they are relatively nearby and isolated, whereas the restrictions are less stringent for larger groups. Specifically, of the  $n_{\min} = 2$  groups, only those with  $z < z_{\max} = 0.07 + 0.02[\log_{10}(L_{bJ}/h^{-2} L_\odot) - 10]$  and having no neighbouring groups with centres at distances less than  $d_{\min}/h^{-1} \text{ Mpc} = 2 + [10 - \log_{10}(L_{bJ}/h^{-2} L_\odot)]$  were used to calculate the mass-to-light ratios.

The reasons for the success of this empirical choice are as follows. Many of the small groups are fragments cleaved from much bigger groups by the group-finding algorithm.



**Figure 12.** The  $r_F$  band equivalent of Fig. 8, showing the ratios of galaxy luminosity functions in the 2PIGG (squares), bumpy mock groups (dotted lines) and superwind mock groups (dashed lines) to the best-fitting Schechter function for the 2PIGGs in each mass range. The mass ranges are:  $M \sim 10^{13} h^{-1} M_\odot$  (left),  $M \sim 10^{14} h^{-1} M_\odot$  (centre) and  $M \sim 10^{15} h^{-1} M_\odot$  (right).



**Figure 11.** The  $r_F$  band equivalent of Fig. 7, showing the STY-determined most likely Schechter function parameters for 2PIGG galaxy luminosity functions. The different group masses are represented by the contours enclosing the open square ( $M = 10^{13.0 \pm 0.5} h^{-1} M_\odot$ ), cross ( $M = 10^{14.0 \pm 0.5} h^{-1} M_\odot$ ) and filled square ( $M = 10^{15.0 \pm 0.5} h^{-1} M_\odot$ ). Results for all galaxies satisfying  $14 < r_F < b_{J,\text{lim}} - 1.5$  and  $z < 0.12$  are shown by contours with no central symbol.

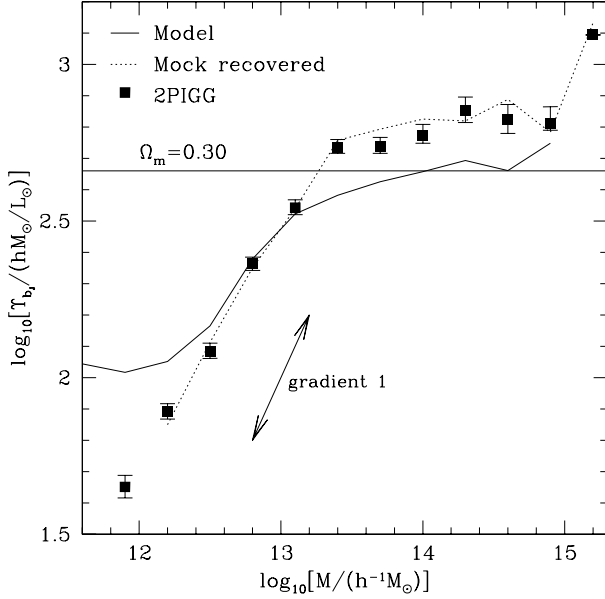
These typically have large velocity dispersions, reflecting the size of the halo to which they really belong. Consequently their mass-to-light ratios are unrepresentatively high. The nearest neighbour distance restriction is intended to eliminate these spurious groups from the analysis. The reason for the redshift limit is the desire that most underlying groups

of a particular size should contain at least two galaxies that will be detected in a flux-limited survey. The mock catalogues used here are such that the true mass-to-light ratio of low luminosity groups is typically lower for groups containing only one detectable galaxy. Thus, in order to ensure that the low luminosity groups are representative of the underlying distribution, only the nearby low luminosity examples are included.

The following two subsections describe the  $b_J$  and  $r_F$  band results. The redder band traces the stellar mass more faithfully than the blue band, and  $\Upsilon_{r_F}$  thus provides additional useful information.

#### 4.1 $b_J$ band results

Fig. 13 shows the dependence of  $\Upsilon_{b_J}$  on group mass. The horizontal line indicates the mean mass-to-light ratio in the mock universe, and the other solid line represents the variation of the median group  $\Upsilon_{b_J}$  with halo mass in the simulation with semi-analytical model galaxies from which the mock catalogues were constructed. A dotted line traces what is actually recovered from the mock catalogue, and the filled squares show the results from the real 2PIGG subsample of groups. Error bars represent the 16th and 84th percentiles divided by the square root of the number of groups in each bin. As a result of the large spread of accuracies in the inferred group masses for groups containing only a few members, there is a strong smearing effect along a line of gradient one. For the highest mass groups, for which more galaxies yield better mass estimates, this trend is reduced, but there is sufficient contamination from low luminosity groups with greatly overestimated masses, that the recovered  $\Upsilon_{b_J}$  is still biased high by 30 – 40 per cent. The main reason why the mock recovered variation resembles the true behaviour in the parent simulation at intermediate masses is that this is where the majority of the groups are found (see Fig. 1), so there are comparable numbers of groups biasing the results

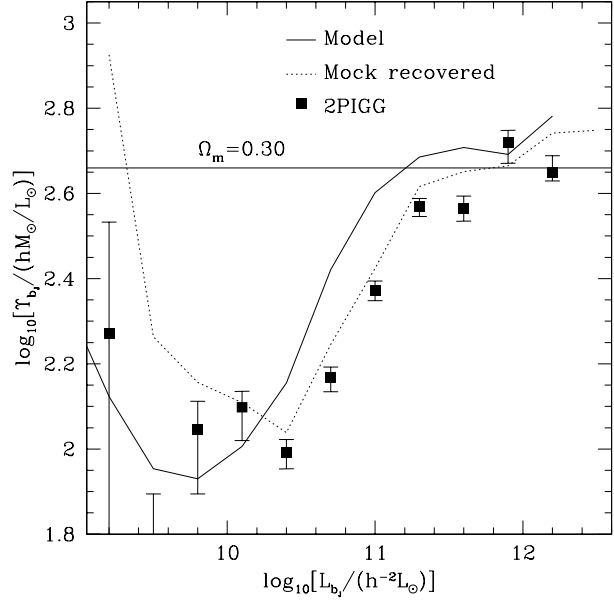


**Figure 13.** The group mass-to-light ratios as a function of group mass. The solid line traces the variation of the median  $\Upsilon_{b_j}$  in the semi-analytical model from which the mock group catalogues were constructed. The dotted line shows the  $\Upsilon_{b_j}$  actually recovered from the mock catalogue using groups with  $n_{\min} = 2$  that lie within a redshift of  $z_{\max} = 0.07 + 0.02 [\log_{10}(L_{b_j}/h^{-2} L_{\odot}) - 10]$  and have no neighbouring groups with centres at distances less than  $d_{\min}/h^{-1} \text{ Mpc} = 2 + [10 - \log_{10}(L_{b_j}/h^{-2} L_{\odot})]$ . The corresponding measurement from the 2PIGG sample is shown by the filled squares, with error bars representing the 16th and 84th percentiles divided by the square root of the number of groups contributing to each bin. This would be the standard deviation on the median if the  $\Upsilon_{b_j}$  values were distributed Normally in each bin. The horizontal line indicates the mean mass-to-light ratio of the mock universe, calculated using the luminosity function of Norberg et al. (2002), and the appropriate value of  $\Omega_m = 0.3$ . A line with gradient 1 is also plotted to illustrate the direction in which errors in the inferred group masses would move the estimated values.

high and low. In summary, this figure demonstrates that it is unhelpful to plot correlated variables when they both suffer from the same large uncertainty.

A much better method for ordering groups in terms of size is to use their measured luminosities; these have much smaller errors than the group masses, particularly for groups with only two members (see Fig. 3). Now, instead of mass errors smearing out the results along a line of gradient one, there are luminosity uncertainties that act along a line of gradient minus one. The sign of this gradient is opposite to the trend of  $\Upsilon_{b_j}$  with halo luminosity in the parent simulation, and the amplitude of this error vector is now substantially reduced. Fig. 14 shows the corresponding variation of group mass-to-light ratio with group luminosity.

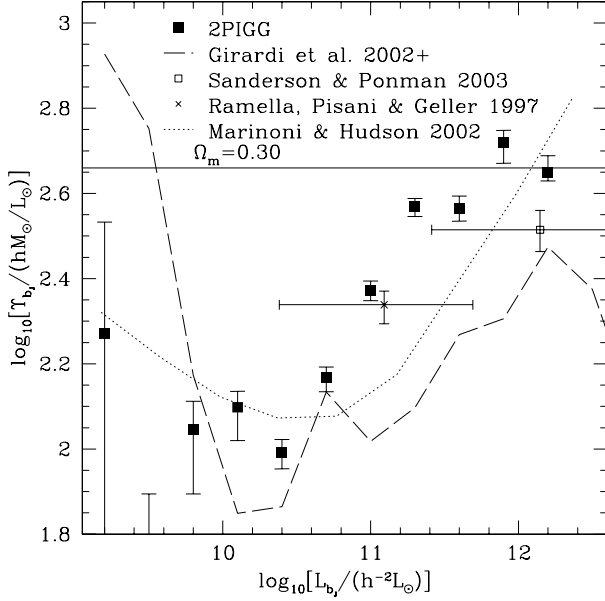
In the semi-analytical model, the variation of  $\Upsilon_{b_j}$  reflects the efficiency of star formation in haloes of different mass. Star formation is most efficient in haloes with  $L \approx 6 \times 10^9 h^{-2} L_{\odot}$ , the point at which the minimum of the solid line occurs. The dotted line traces the variation of  $\Upsilon_{b_j}$  recovered from the group mock catalogue. It



**Figure 14.** The median mass-to-light ratio of groups as a function of group luminosity. Line types and symbols are the same as in the previous figure, as are the values of  $n_{\min}$ ,  $z_{\max}$  and  $d_{\min}$  defining the recovered groups.

is immediately apparent that this recovery, for haloes with  $L_{b_j} \gtrsim 10^{10} h^{-2} L_{\odot}$ , is very much better than was the case when group mass was used to quantify halo size. In particular, both the rise in  $\Upsilon_{b_j}$  from small groups to clusters, and the plateau for the largest clusters are well reproduced. There is a slight bias low, by  $\sim 40$  per cent, during the rise. This can be understood in terms of the position of the peak in the distribution of groups as a function of luminosity (Fig. 2), and the typical errors being made, whereby luminosities are slightly overestimated as a result of contamination (Fig. 4). The recovery of the mass-to-light ratio for groups less luminous than  $L_*$  (for galaxies) is poor. Among the reasons for this is the fact that the individual redshift measurement errors become comparable with the typical group velocity dispersions in such small systems. Also, there is insufficient volume to achieve small statistical errors while ensuring that these groups contain more than one detectable galaxy.

For the 111 groups with  $\log_{10}[L_{b_j}/(h^{-2} L_{\odot})] > 11.5$  in the mock catalogue, the recovered median and mean mass-to-light ratios are  $471$  and  $549 \pm 28 h M_{\odot}/L_{\odot}$  respectively. The corresponding values in the parent simulation are  $507$  (median) and  $520$  (mean). Thus, the mean is overestimated in the mocks by  $\sim 6$  per cent, while the recovered median is  $7$  per cent too low. As the mean is more easily affected by outlying data points with high measurement errors, in what follows only the median cluster mass-to-light ratio will be used. The estimate of  $\Omega_m$  from the cluster mass-to-light ratio is based on comparing this to the mean mass-to-light ratio of the universe. In the parent simulation, the mean universal value is  $458 h M_{\odot}/L_{\odot}$ ,  $10$  per cent lower than the median recovered mass-to-light ratio of clusters. Thus, for this mock catalogue at least, the median mass-to-light ratio



**Figure 15.** The median mass-to-light ratio of groups as a function of group luminosity. As in the previous figure, filled squares represent results for the 2PIGG sample. The horizontal line indicates the mean mass-to-light ratio determined from the mean luminosity density of Norberg et al. (2001), assuming  $\Omega_m = 0.3$ . The results of four other studies of B-band group mass-to-light ratios are also shown, as indicated in the legend. Vertical error bars on the data points give the uncertainty on the median  $\Upsilon_{b_j}$ . The horizontal error bars represent the 16 – 84 percentile range of the group luminosities contributing to these medians.

of the recovered clusters allows a pretty accurate estimate of the mean mass density of the simulated universe.

The filled squares with error bars in Fig 14 represent the real 2PIGG mass-to-light results. These are remarkably similar to what was recovered from the mock catalogue, showing the same three basic features: nothing useful at  $L \lesssim 10^{10} h^{-2} L_\odot$ , a rise by a factor of  $\sim 5$  up to  $L \sim 2 \times 10^{11} h^{-2} L_\odot$ , and a constant mass-to-light ratio for the largest groups. Unlike the case when mass was used to quantify the group size, this trend of increasing median mass-to-light ratio with larger groups can no longer be confused with the effect of mass measurement errors. For the  $\log_{10}[L_{b_j}/(h^{-2} L_\odot)] > 11.5$  groups, of which there are 96, the median  $\Upsilon_{b_j} = 429 \pm 25 h M_\odot/L_\odot$ , where the uncertainty represents the statistical error on the median. This number is used later to estimate  $\Omega_m$ .

## 4.2 Comparison with other studies

When comparing these results with other studies, it is essential to bear in mind that there exists a variety of definitions of a group. To reiterate, the 2PIGG analysis is designed to recover, as well as possible, groups that resemble those identified in a  $\Lambda$ CDM dark matter simulation using the standard linking length of 0.2 times the mean interparticle separation. Note that in Fig. 15, the raw 2PIGG results are shown for the purpose of comparison with other studies, despite the fact that they probably suffer from a small bias of the sort

shown in Fig. 14. In Section 4.4, this bias is corrected and functions are given which describe the variation of the corrected median group mass-to-light ratio with group luminosity.

The results of Girardi et al. (2002; G2002), which extend the database used by Girardi et al. (2000) with groups mostly found in the Nearby Optical Galaxy (NOG) catalogue, contain groups from a number of different surveys. Note that these papers both contain a typo relating to the conversion between  $B$  and  $b_J$  magnitudes (Girardi, private communication). The correct relation, for a mean galaxy colour of  $(B - V) = 0.9$ , is

$$B - b_J = 0.252. \quad (4.1)$$

In conjunction with

$$(B - b_J)_\odot = 0.15, \quad (4.2)$$

this leads to

$$\left(\frac{L}{L_\odot}\right)_{b_J} = 1.1, \quad (4.3)$$

as was correctly reported in G2002. Fig. 15 shows the data from the (CL+PS) sample of G2002, supplemented with 500 other systems from their set of groups found by applying a percolation algorithm to the NOG survey (Girardi, private communication). Relative to the homogenous 2PIGG sample, this set of groups comes from a number of different sources and, furthermore, they were analyzed using different types of mass and luminosity estimators. Yet, a broadly similar behaviour of the mass-to-light ratio is seen. Care is needed, however, because the percolation algorithm of G2002 will presumably yield results that are biased to low mass-to-light ratios, for the same reason that the 2PIGG results are affected. Their percolation algorithm (Giuricin et al. 2000) employs a scaling of the linking volume with redshift that is different from that used for the 2PIGG catalogue (Eke et al. 2004), so the properties of the recovered groups will be different.

Sanderson & Ponman (2003) used a sample of 32 systems with masses inferred from their X-ray emission. These groups are concentrated towards the large mass end of the distribution and show little or no trend of mass-to-light ratio with group luminosity, comparable with the 2PIGG results. Again, their results yield slightly lower values of the mass-to-light ratio than found for 2PIGG. Note that the point plotted in the figure differs very slightly from that in the Sanderson & Ponman paper as a result of the correction of an error in their  $B$  to  $b_J$  conversion for 3 groups.

Ramella, Pisani & Geller (1997) used a sample of 406 groups identified in the northern CfA2 survey, with masses estimated from optical data. While the median mass-to-light ratio is lower than that of the Sanderson & Ponman groups, the CfA2 groups are typically smaller and the 2PIGG results indicate that  $\Upsilon_{b_j}$  should be smaller for such groups. However, once more, the mass-to-light ratio in this sample is lower than that inferred from the 2PIGG catalogue.

Marinoni & Hudson (2002) have indirectly inferred a mass-to-light ratio variation for groups by finding the mapping between the Press-Schechter (1974) mass function, for some assumed cosmological model, and the luminosity func-

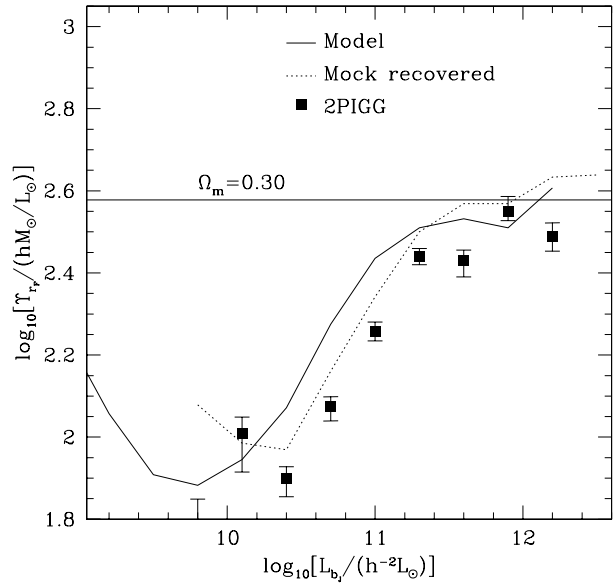
tion of groups measured from the NOG sample by Marinoni et al. (2002). Their results are given in the  $B$  band, and have been converted to the  $b_J$  band using equation (4.3). This curve shows a similar trend to the 2PIGG results but, again, with an offset. In general, estimators of the luminosity function of groups tend to be biased towards high luminosities as a result of the inevitable inclusion of interlopers in the groups, the statistical errors in the inferred group luminosities and the steep decline in the abundance of objects with increasing size. This would lead to an overestimate of the luminosity at a particular abundance (or mass), biasing low the inferred mass-to-light ratio. Indeed, estimating the luminosity function of groups in mock 2PIGG catalogues suggests that this bias could plausibly yield an overestimate of the group luminosity by a factor of at least 2 at a particular abundance (Eke et al. in preparation). If a similar size of bias were present in the sample used by Marinoni & Hudson, then this would account for their significantly lower mass-to-light ratios at  $L \sim 10^{11} h^{-2} L_\odot$ .

One factor that would bias the 2PIGG mass-to-light values slightly high is the incompleteness in the parent 2dFGRS catalogue (Pimblet et al. 2001; Norberg et al. 2002; Cross et al. 2004). Such an effect, however, is small compared to the difference between the 2PIGG results and those of the other studies shown in Fig. 15. The most likely other reason why the 2PIGG results could be systematically incorrect is if the mass estimator employed here is not appropriate in the real world, as discussed in Section 2. This would happen if galaxies traced real dark matter haloes in a different way from what was assumed in making the mock catalogues, either because they had a different velocity dispersion to the underlying dark matter, or because they had a different projected spatial distribution (De Lucia et al. 2004; Diemand, Moore & Stadel 2004). In order for biases of this kind to give rise to the observed variation of the mass-to-light ratio with group size, however, they would need to depend very strongly on group size. It is difficult to imagine that such biases could give rise to the factor of  $\sim 5$  variation seen in the data.

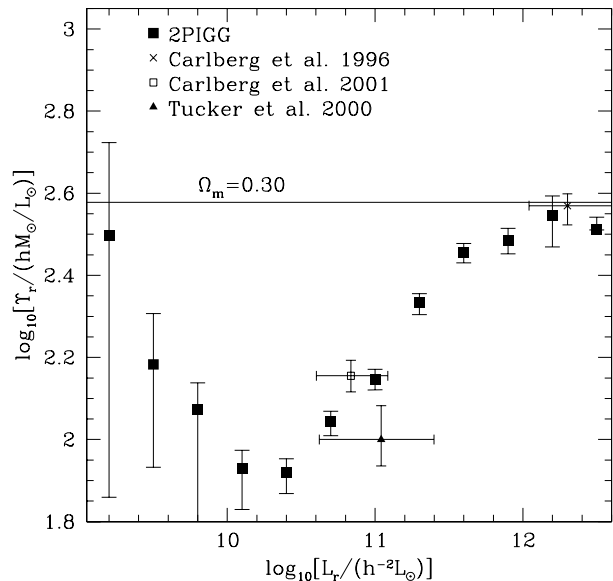
### 4.3 $r_F$ band results

As described in Appendix A, the 2dFGRS combined with the SuperCOSMOS  $r_F$  data provides a well defined sample of galaxies with  $14 < r_F < b_{J,\text{lim}} - 1.5$ . While applying these flux limits reduces the number of galaxies available to calculate the group luminosity, the missing faint galaxies contribute little to the total, so the accuracy with which group  $r_F$  band luminosities can be inferred is comparable to that for the  $b_J$  band, as was shown in Section 2.2.

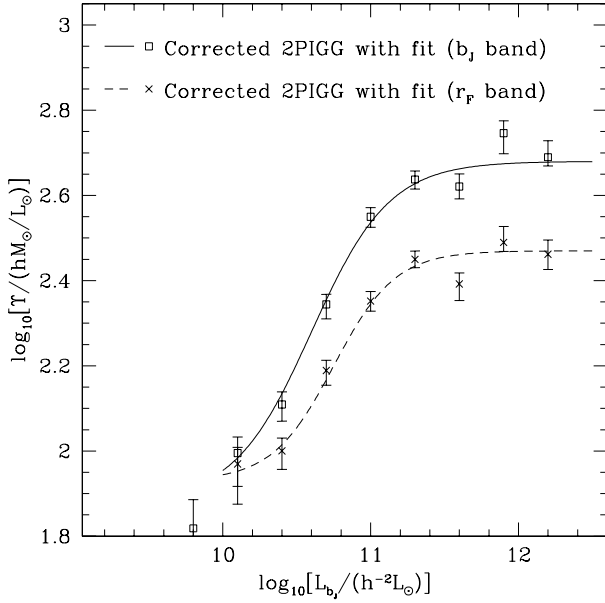
Fig. 16 shows how well the variation of  $\Upsilon_{r_F}$  in the parent simulation can be recovered in the mock catalogue, as a function of group  $b_J$  luminosity. (This is a slightly better determined measure of 2PIGG size than the  $r_F$  luminosity.) The results are remarkably similar to those shown in Fig. 14 for  $\Upsilon_{b_J}$ . Firstly, the intrinsic variation present in the parent simulation is quite accurately recovered in the mocks. Secondly, as was the case for  $\Upsilon_{b_J}$ , the 2PIGG data agree remarkably well with the behaviour seen in the mock catalogue. The main difference between the  $r_F$  and  $b_J$  results is the size of the change in typical mass-to-light ratio over the reliably probed range of group luminosities. This is not as



**Figure 16.** The variation of the  $r$  band group mass-to-light ratio with group  $b_J$  luminosity. A solid line traces the median behaviour in the parent simulation, and the dotted line shows what is actually recovered in the mock catalogue. Filled squares represent the results from the 2PIGG catalogue, using the same redshift and minimum group separation as were applied to the  $b_J$  band data.



**Figure 17.** The variation of the  $r_F$  band group mass-to-light ratio with group luminosity. Filled squares represent the results from the 2PIGG catalogue, and the other symbols show other observational determinations, as detailed in the legend. Note that the Carlberg et al. results have luminosities measured in the Gunn  $r$  band, and the Tucker et al. data are in the LCRS  $R$  band.



**Figure 18.** The corrected variation of the 2PIGG group mass-to-light ratio with group luminosity, in both the  $b_J$  and  $r_F$  bands. Equations (4.4) for  $\Upsilon_{b_J}$  and (4.5) for  $\Upsilon_{r_F}$  are shown as solid and dashed lines. The corresponding 2PIGG data are shown with open squares and crosses.

extreme in the  $r_F$  band, a factor of  $\sim 3.5$  rather than the factor of  $\sim 5$  seen in the  $b_J$  band – as one would expect if halo size has a stronger effect on recent star formation than on the overall stellar mass.

Fig. 17 compares the 2PIGG results with those from CNOC groups and clusters (Carlberg et al. 1996, 2001) and the LCRS groups (Tucker et al. 2000). Unlike in the  $b_J$  band case, there is now some agreement between the 2PIGGs and some other work. Note that the Carlberg et al. data points have luminosities measured in the Gunn  $r$  band and include a correction to redshift zero, whereas the Tucker et al. data are measured in the LCRS  $R$  band. Once again, the horizontal error bars illustrate the 16 – 84th percentile range in group luminosity contributing to each point.

#### 4.4 Corrected mass-to-light results

It was shown in Sections 4.1 and 4.3 that the values of  $\Upsilon$  as a function of  $L_{b_J}$  recovered in the mock catalogues are slightly biased low relative to the values in the parent simulation. This bias is reproducible in mocks constructed from other simulations, for example, from the less clustered mass distribution of a  $\Lambda$ CDM simulation with  $\sigma_8 \approx 0.7$  analyzed at  $z \approx 0.1$  (rather than the default simulation with  $\sigma_8 = 0.9$  and  $z = 0.1$ ).

It seems plausible that a bias of this kind is also present in the 2PIGG sample results. A correction factor is defined as the ratio between the luminosity-dependent values of  $\Upsilon$  measured in the parent simulation and in the mocks (in both the  $b_J$  and  $r_F$  bands). The 2PIGG results are simply multiplied by this factor to obtain an estimate of the true underlying group mass-to-light ratio variation in the real Universe. The corrected values are shown with open squares ( $b_J$  band)

and crosses ( $r_F$  band) in Fig. 18. The error bars on the data points still represent the size of the statistical uncertainty on the median. Approximate fits to the corrected 2PIGG median mass-to-light ratios are shown by the solid ( $b_J$ ) and dashed ( $r_F$ ) lines, which have the following functional forms:

$$\log_{10} \Upsilon_{b_J} = 2.28 + 0.4 \tanh\{1.9 [\log_{10}(L_{b_J}) - 10.6]\} \quad (4.4)$$

and

$$\log_{10} \Upsilon_{r_F} = 2.20 + 0.27 \tanh\{2.4 [\log_{10}(L_{b_J}) - 10.75]\}. \quad (4.5)$$

These equations are valid for  $10 \leq \log_{10}(L_{b_J}/h^{-2} L_\odot) \leq 12.5$ . Since the 2PIGG results are so similar to those recovered from the mock catalogue, these fits to the underlying ‘truth’ in the real Universe also provide a decent description of the behaviour in the parent simulation, as traced by the solid lines in Figs 14 and 16. The correction is sufficiently small that all the basic features of the results discussed above remain.

The correction changes the median mass-to-light ratio of the 98 clusters with  $\log_{10}[L_{b_J}/(h^{-2} L_\odot)] > 11.5$  from  $\Upsilon_{b_J} = 427 \pm 24 h M_\odot/L_\odot$  to  $466 \pm 26 h M_\odot/L_\odot$ . Together with the global mean  $b_J$  band luminosity density and its uncertainty, inferred from the luminosity function measured by Norberg et al. (2002), this implies\* that  $\Omega_m = 0.31 \pm 0.03$ . If, as was the case in the mocks, the median mass-to-light ratio of the largest clusters overestimates the mean mass-to-light ratio of the Universe by  $\sim 11$  per cent, then this estimate should come down accordingly to  $\Omega_m = 0.28 \pm 0.03$ . This uncertainty only includes the statistical error.

Possible sources of systematic uncertainty, in addition to the two model-dependent corrections already applied to the raw 2PIGG results, would come from systematic errors in the estimation of the cluster mass-to-light ratios. These could arise from the underestimate of the cluster luminosities resulting from incompleteness in the parent 2dFGRS catalogue. In fact, Norberg et al. (2002) do assume a 9 per cent incompleteness in the 2dFGRS parent catalogue when computing the mean  $b_J$ -band luminosity density of the Universe, so for consistency the 2PIGG luminosities should be similarly increased. The resulting lower mass-to-light ratios yield  $\Omega_m = 0.26 \pm 0.03$ . Another, less readily quantified, potential systematic uncertainty would come from a bias in the mass estimator if real galaxies do not trace dark matter haloes in the way assumed in the mocks. As discussed in Section 2 this could plausible be a few tens of per cent.

It is interesting that both this estimate of  $\Omega_m$  and its statistical uncertainty are very similar to the values quoted by Spergel et al. (2003) from the combination of WMAP microwave background data and the 2dFGRS galaxy power spectrum. This agreement, in itself, suggests that the systematic uncertainties in either estimate are likely to be small and provides a welcome consistency check of the entire paradigm of structure formation by hierarchical clustering from CDM initial conditions. Further reassurance can be gained from using the  $r_F$ -band mass-to-light ratios of the

\* Assuming that the galaxies trace the mass in clusters, as is customary when using this method

same set of the most luminous clusters and the  $r_F$ -band luminosity density of the Universe (see Appendix A). This yields an estimate of  $\Omega_m = 0.25 \pm 0.04$ , which is consistent with the value inferred from the  $b_J$ -band data.

## 5 CONCLUSIONS

This paper presents an analysis of the galactic content of the 2PIGG catalogue of groups and clusters identified in the 2dFGRS, focusing on the galaxy luminosity function and total mass-to-light ratio in groups of different size in both the  $b_J$  and  $r_F$  bands. In constructing the 2PIGG catalogue (Eke et al. 2004) and in the present analysis, a well defined methodology has been followed based on the extensive use of mock catalogues. The starting points are N-body simulations of the evolution of dark matter in a  $\Lambda$ CDM universe in which model galaxies are added with properties calculated according to a semi-analytical model of galaxy formation based on the precepts laid out in Cole et al. (2000). The parent simulation provides a full description of the model galaxy distribution, free from the distortions inevitably introduced by observational procedures, such as selection effects, observational errors, etc. These distortions are modelled carefully in order to generate mock catalogues that correspond to artificial 2dFGRSs. Since the properties of the parent simulation are known, the mock catalogues provide a rigorous way to quantify the systematic uncertainties in the derived properties of interest as well as a good guide to possible systematic errors. Of course, the mock catalogues also enable a detailed comparison between the real data and the model from which the mocks were generated.

The main results of this paper are:

- (1) The galaxy luminosity function is different in groups of different mass. These luminosity functions are moderately well described by Schechter functions for which, as the group mass increases, the characteristic luminosity,  $L_*$ , increases and the faint end slope,  $\alpha$ , becomes more negative. However, the galaxy luminosity functions in the groups found in the original simulations are not well described by Schechter functions. For example, they exhibit a ‘bump’ at the bright end whose amplitude varies with group mass reflecting the relative importance of the central galaxy and the satellites in the groups. Hints of bumps are also found in the largest 2PIGG clusters.
- (2) The median group mass-to-light ratio,  $\Upsilon$ , also varies with halo size (which is most robustly characterized by total  $b_J$  halo luminosity). The mock catalogues indicate that, in the 2PIGG catalogue,  $\Upsilon$  is reliably determined for groups of size ranging from that of the Local Group to the richest clusters in the survey. Over this range, which extends from  $L_{b_J} = 10^{10} h^{-2} L_\odot$  to  $L_{b_J} = 10^{12} h^{-2} L_\odot$ ,  $\Upsilon_{b_J}$  increases by a factor of 5 whereas  $\Upsilon_{r_F}$  increases by a factor of 3.5. At the highest luminosities,  $\Upsilon$  becomes roughly constant in both bands. The semi-analytical models predict an upturn in  $\Upsilon$  at luminosities lower than  $L_{b_J} \sim 10^{10} h^{-2} L_\odot$  at which galaxy formation is most efficient. Unfortunately, the 2PIGG catalogue does not contain enough small groups with sufficiently accurate estimates of  $\Upsilon$  to locate the theoretically expected minimum.
- (3) For the  $L_{b_J} > 3 \times 10^{11} h^{-2} L_\odot$  objects, the median mass-to-light ratio is  $\Upsilon_{b_J} = 466 \pm 26$  (statistical)  $h M_\odot/L_\odot$ , in-

dependently of cluster size. Assuming that this value reflects the cosmic mean (i.e. that  $\Upsilon$  in these richest clusters has converged to the global value) allows a determination of the mean cosmic density,  $\Omega_m$ . Adopting the  $b_J$  luminosity density inferred from the 2dFGRS galaxy luminosity function by Norberg et al. (2002), leads to  $\Omega_m = 0.26 \pm 0.03$ . (This estimate includes two small corrections derived from the mock catalogues as discussed in Section 4.4, and a third small correction for incompleteness in the 2dFGRS parent catalogue.) This value and its uncertainty are in excellent agreement with the values inferred by Spergel et al. (2003) from a combination of microwave background data and the galaxy power spectrum in the 2dFGRS.

The agreement of the 2PIGG results with the predictions of the simulations is impressive, and provides confidence in the basic picture of galaxy groups tracing virialized haloes of dark matter. The simulations suggest two fruitful avenues for improving upon this work: (i) probe smaller groups to test whether the  $M/L$  ratio does indeed pass through the expected minimum around a group mass of  $10^{12} h^{-1} M_\odot$ ; (ii) create catalogues with better resolved groups to see if the non-Schechter nature of the theoretically predicted luminosity functions can be revealed. Both these targets will require new large redshift surveys that probe substantially further down the luminosity function than is possible with the current dataset.

## ACKNOWLEDGEMENTS

The 2dF Galaxy Redshift Survey was made possible through the dedicated efforts of the staff of the Anglo-Australian Observatory, both in creating the 2dF instrument and in supporting it on the telescope. VRE and CMB are Royal Society University Research Fellows. PN is a Zwicky Fellow. JAP is a PPARC Senior Research Fellow.

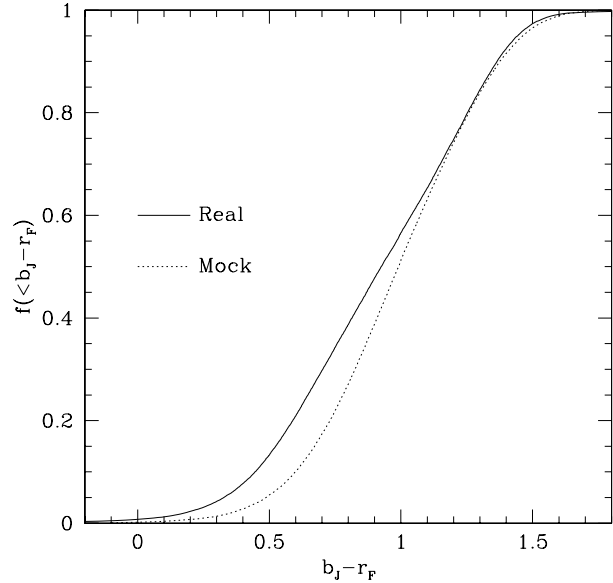
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## APPENDIX A: CALCULATING GROUP $r_F$ LUMINOSITIES

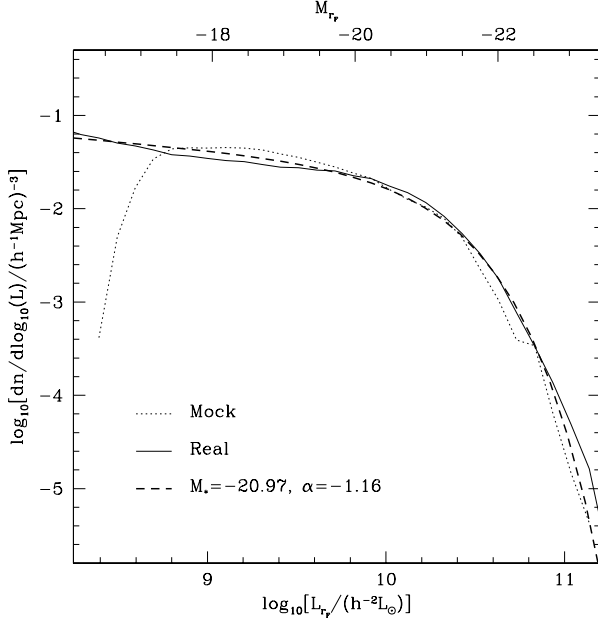
As the 2dFGRS is a  $b_J$  selected survey, extra consideration is required in order to include the SuperCOSMOS  $r_F$  band data in the analysis. For instance, it is necessary to determine an appropriate local flux limit to which the  $r_F$  band data are complete. The term complete is used here without reference to the well-quantified incompleteness in the redshifts measured for objects in the 2dFGRS parent catalogue, and the possible incompleteness in the parent catalogue itself. A local  $r_F$  band flux limit is determined from



**Figure A1.** The cumulative distribution of galaxy  $b_J - r_F$  values for all  $z < 0.12$  galaxies in the 2dFGRS (solid line) and mock (dotted line) catalogues.

the distribution of observed galaxy colours. Fig A1 shows the cumulative distribution of the galaxy  $b_J - r_F$  values for the sets of  $z < 0.12$  galaxies in both the mock and the 2dFGRS data. As at least 95 per cent of galaxies are bluer than  $b_J - r_F = 1.5$ , the local minimum  $r_F$  band flux limit is set equal to  $r_{F,\text{lim}} = b_{J,\text{lim}} - 1.5$ . From this figure, one can also infer that the bright  $b_J > 14$  limit can essentially be transferred into the  $r_F$  band, such that the  $r_F$  band sample is also complete for  $r_F > 14$ . Thus, a ‘complete’  $r_F$ -limited sample can be made to a locally defined flux limit corresponding to  $14 < r_F < b_{J,\text{lim}} - 1.5$ . This lower flux limit removes about 29 per cent of the galaxies from the sample, whereas only  $\sim 0.4$  per cent were discarded for being brighter than the upper flux limit.

Having found flux limits defining a complete  $r_F$  band sample, the intention is, as before, to tot up the galaxy luminosities taking into account the weights associated with the redshift incompleteness, and then apply the appropriate Schechter function correction for the galaxies that are too faint to make the flux cut. However, the galaxies included above the  $r_F$  flux limit are now a bright subsample of the 2dFGRS parent catalogue. Thus, they are no longer drawn from the same population as the subsample of parent catalogue galaxies without measured redshifts, and so equation (2.2) is no longer an unbiased way to correct for this redshift incompleteness. This complication was sidestepped by redistributing only the weights of galaxies without redshifts and with  $14 < r_F < b_{J,\text{lim}} - 1.5$ . Thus, the subsample of galaxies with redshifts and sufficiently high  $r_F$  band fluxes is now a similar population to those galaxies without redshifts whose weights are redistributed. As only about 2/3 of the 2dFGRS galaxies satisfy the  $r_F$  flux limits, the weights were redistributed to the nearest 7 projected galaxies only. This should match the angular smoothing scale with that used in the  $b_J$  band.



**Figure A2.** The  $r_F$  band luminosity functions, estimated using a  $1/V_{\max}$  method, for all  $z < 0.12$  galaxies in the mock (dotted line) and 2dFGRS (solid line). The dashed line shows the suitably normalised Schechter function resulting from an STY fit to the 2dFGRS data.

In addition to the correction for redshift incompleteness, galaxies below the flux limit also need to be accounted for in determining the total group luminosity. This was accomplished by assuming that the galaxy luminosity function in the groups can be fitted by a Schechter function with  $(M_*, \alpha) = (-20.97, -1.16)$ . This is the STY-estimated Schechter function for the  $r_F$  band galaxy luminosity function of all  $z < 0.12$  galaxies in the 2dFGRS. In calculating this, the following  $k+e$ -correction, derived using Bruzual & Charlot (1993) models, was used:

$$k + e = \frac{z + 2z^2}{1 + 9z^{2.5}}. \quad (\text{A1})$$

Choosing a normalisation to match the luminosity function amplitude inferred using a  $1/V_{\max}$  estimator leads to  $\phi_* = (1.2 \pm 0.1) \times 10^{-2} (h^{-1} \text{Mpc})^{-3}$ . This value, which neglects the incompleteness in the parent catalogue of the 2dFGRS, gives a mean  $r_F$  luminosity density in the Universe of  $\rho_{r_F} \approx 2.2 \times 10^{-2} h L_\odot \text{Mpc}^{-3}$ . As can be seen in Fig. A2, the  $r_F$  band luminosity functions estimated using the  $1/V_{\max}$  method are similar in the 2dFGRS and the mock catalogue (which yields  $M_* = -20.79$  and  $\alpha = -1.17$ ). For the  $r_F$  band,  $M_\odot = 4.57$ .